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16. SUPPLEMENTARY NOTATION: A more complete title of the program is: Low Density and Tough Steels with High Hardenability: Processing, Testing and Evaluation of UHC steels and their laminates

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19. ABSTRACT

It is proposed that major development efforts on ultrahigh carbon steels (UHCS) and their laminates are timely and programs to evaluate prototype structural components should be initiated. The hardenability of fine grained UHC steel is improved by dilute alloying additions of manganese, aluminum and nickel. The impact resistance of UHCS laminated composites, after selective heat treatment, can be enhanced by appropriate choice of interleaf material. Two factors are important: the interlayer boundary should be discrete and the interleaf material should be notch ductile. Several interleaf materials have been investigated including Fe-3Si, Hadfield manganese steel, 304 stainless steel, Fe-9Ni-2Si and brass.

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LOW DENSITY AND TOUGH STEELS WITH HIGH HARDENABILITY: PROCESSING, TESTING AND EVALUATION OF UHC STEELS AND THEIR LAMINATES
(DAAG-29-84-K-0190)

FINAL REPORT (August 1984 - November 1989)
by
Oleg D. Sherby

This final report summarizes the work accomplished during the period August 1984 to November 1989 on the above program on ultrahigh carbon steels (UHCS) and their laminates. The program was sponsored and monitored by the Army Research Office under Contract DAAG-29-84-K-0190. Close collaboration was maintained with researchers from a number of army laboratories including AMTL, TACOM, BRL, ARDC, as well as with researchers and managers from DARPA, LLNL and SRI International. Funding in various forms was received from the army laboratories, from DARPA and from LLNL. A description of the interactions and funding related to the various laboratories and agencies are documented in the ten semi-progress reports prepared on the program. The project monitors were Dr. George Mayer and Dr. Iqbal Ahmad of the ARO office. The author and his colleagues would like to express their appreciation to Drs. Mayer and Ahmad for their encouragement and cooperation throughout the course of this program. Their technical interest in our work, as well as their guidance, helped to optimize and complete our research work toward understanding the mechanical behavior of UHCS and their laminates.

1. Statement of the Problem Studied

The two principal objectives of the ARO program, in the initial phase, were as follows: (1) establish a method of producing light and tough steel through solid-state bonding, and (2) enhance hardenability of such steels through dilute alloying additions. As the program progressed two new objectives were added as follows: (3) evaluate and test UHC steels in sections that are sufficiently large so that a reliable data base can be developed on their mechanical and structural characteristics, and (4) manufacture laminated composites

of UHC steel with interleaf materials that can be expected to yield promising notch impact properties in the resulting composites.

2. Interaction with various organizations on the program

Many meetings were held, at Stanford and at other organizations, on the subject of UHC steels and their laminates with respect to the studies achieved on this program. The following agencies and personnel contributed, in a number of important ways, to these meetings and to the continuity of the program: (1) DARPA : Drs. William Snowden, Richard Reynolds, Ben Wilcox and Phil Parrish, (2) AMTL (formerly AMMRC): Mr. Morris Azrin, Mr. Timothy Thomas, Dr. Richard Chait, Dr. Ed Wright, Dr. Ralph Adler, Dr. Eric Kula, Dr. Gordon Bruggeman, Dr. George Bishop, Mr. M. Stacher, Mr. John Graves, Mr. Ray Singleton, and Dr. Dino Papetti (3) ARDC: Dr. Sheldon Cytron and Dr. Ernest Bloore, (4) BRL: Dr. Andrew Dietrich, Dr. Gerald Moss and Mr. Edward Horwath (5) TACOM: Mr. James Ogilvy, (6) LLNL: Drs. Alfred Goldberg and Don Lesuer, and Mr. Paul Adler and (7) SRI International: Dr. Robert Caligiuri and Lawrence Eiselstein. Other contributors were Dr. Don Koistinen, Dr. Michael Shea, and Mr. Ed Mantell (G.M. Technical Center), Dr. Don Sherman (Caterpillar Research Laboratory), Dr. S. Rajagopal (FMC R. and D. center), Dr. Arden Bement (TRW), Drs. Bruce Bramfitt and Charles Apple (Bethlehem's Homer Research Laboratory), Dr. Dillip Subramanyan (ABEX), and Mr. Ray Cellitti (R.C. Associates). All the meetings, held at Stanford, AMTL, DARPA headquarters, LLNL, SRI Intn., and the Homer Research Laboratory, were attended either by Dr. George Mayer or Dr. Iqbal Ahmad of the ARO office.

3. Summary of the Most Important Results

The hardenability of fine grained UHC steels can be improved by dilute alloying additions. Manganese, aluminum and nickel are shown to be very effective in improving the hardenability of UHC steels. The impact resistance of UHCS laminated composites, after selective heat treatment, can be enhanced by appropriate choice of interleaf material. Two factors are important: the interlayer boundary should be discrete and the interleaf material should be notch ductile. Discrete boundaries can be readily achieved if carbon interdiffusion is inhibited during selective heat treatment. Several interleaf materials have been investigated including Fe-3Si, Hadfield manganese steel, 304 stainless steel, Fe-9Ni-2Si and brass. Large

three layer laminated composites, based on high hardenable UHC steel, have been successfully processed by a press-bonding procedure.

Although metal matrix composites have been studied extensively for the past twenty years, the specific area of metal matrix laminated composites (MMLC) seems to have been mostly ignored. Laminated composites based on UHCS, however, have a rich and fascinating history, and dates back to antiquity. For example, welded damascus steel, as well as ancient Japanese weapons, were based on laminating UHCS with low carbon steel. The research at Stanford University on UHCS laminates has revealed that the production of laminates is enhanced when the grain size is fine in the UHCS. This unique characteristic permits the manufacture of laminated composites at low temperatures with the resulting opportunity of developing unique combinations of interleaf materials (e.g. UHCS and brass) with discrete interlayer boundaries. The high notch impact resistance that can be achieved in UHCS laminated composites is impressive, with the DBTT being below - 150 C. It is timely to consider major development efforts on UHCS and their laminates, and programs to evaluate prototype structural components should be initiated. Research activities into assessing the influence of number of layers (i.e. layer thickness) on the mechanical properties of MMLC materials is also a very important area worthy of exploration.

3. List of publications and theses on the technical program

A. Publications

(1) "Ultrahigh Carbon Steels" by O.D. Sherby, T. Oyama, D.W. Kum, B. Walser and J. Wadsworth, Journal of Metals, June 1985, 50-56.

(2) " Superplastic Ultrahigh Ca[illegible] Steels" by D. W. Kum, T. Oyama, O. D. Sherby, O.A. Ruano and J. Wadsworth, In Superplastic Forming, Metals/Materials Technology Series, ASM International, Metals Park, Ohio, 44073 (1985).

(3) "Damascus Steels", by O.D. Sherby and J. Wadsworth, Scientific American, 252, February 1985, 112-120.

(4) "Welded Damascus Steels and a New Breed of Laminated Composites", by Jeffrey Wadsworth, Dong Wha Kum and

Oleg D. Sherby, Metal Progress, June 1986; also published in The Anvil's Ring, Spring 1987 issue.

(5) "Factors Influencing the Fatigue Behavior of Ferrous Laminates", by J. Wittenauer and O.D. Sherby, Trans. ASME, 109, 1987, 244.

(6) "Bulk Forming of Superplastic Alloys", by Oleg D. Sherby and Robert D. Caligiuri, AGARD/NATO Lecture Series 154, 1987.

(7) "Superplasticity in Iron-base Alloys", by Oleg D. Sherby, Jeffrey Wadsworth and Robert D. Caligiuri, in Appendix to Superplastic Sheet Forming, Metals Handbook, 9th Edition, 14, Forming and Forging, ASM Intn, 1988.

(8) "Ultrahigh Carbon Steels" by Oleg D. Sherby and Jeffrey Wadsworth, in Encyclopedia of Materials Science and Engineering, Supplementary Volume 1, Pergamon Press, 541, 1988.

(9) "Superplasticity in Iron-Based Alloys" by Oleg D. Sherby and Jeffrey Wadsworth, in Encyclopedia of Materials Science and Engineering, Supplementary Volume 1, Pergamon Press, 519, 1988.

(10) 'Damascus Steels" by Jeffrey Wadsworth and Oleg D. Sherby, in Encyclopedia of Materials Science and Engineering, Volume 1, Pergamon Press, 113, 1988.

(11) "Properties and Applications of Ultrahigh Carbon Steel Laminates", by R.D. Caligiuri, L.E. Eiselstein and O.D. Sherby, to be published, presented at Sagamore Conference on Materials, 1987.

(12) "Steel" by Oleg D. Sherby and Jeffrey Wadsworth, in McGraw-Hill Yearbook of Science and Technology, 378, 1989.

(13) "Advances in Superplasticity and in Superplastic Materials", by Oleg D. Sherby, ISIJ International, 29, 698, 1989.

(14) " Impact Properties of a Laminated Composite Based on Ultrahigh Carbon Steel and Hadfield Manganese Steel", by Shyong Lee, J. Wadsworth and Oleg D. Sherby, submitted for publication, Res Mechanica (1989).

(15) " Tensile Properties of Laminated Composites based on Ultrahigh Carbon Steel" by Shyong Lee, Jeffrey Wadsworth and Oleg D. Sherby, submitted to Jounal of Composite Materials, 1989.

(16) "Impact Properties of a Laminated Composite based on Ultrahigh Carbon Steel and a Ni-Si Steel", by Shyong Lee, Jeffrey Wadsworth and Oleg D. Sherby, submitted for publication, 1990.

B. Theses

(1) " Factors Influencing the Fatigue Behavior of Ferrous Base Laminated Composites" by Jerome P. Wittenauer, Ph.D. thesis, July 1987.

(2) " Superplasticity and Stability in Metal-Base Composites", by Glenn Daehn, Ph.D. thesis, December 1987.

(3) " Tensile and Impact Behavior of Laminated Composites based on Ultrahigh Carbon Steel", by Shyong Lee, Ph.D. Thesis, September 1988.

4. List of all Participating Personnel and Degrees Received

Professionals

Dr. Oleg D. Sherby, Principal Investigator and Professor

Dr. Jeffrey Wadsworth, Consulting Professor

Dr. Soon Hong, Post-doctoral Fellow

Dr. Toshi Oyama, Post-doctoral Fellow

Dr. Jeffrey Wolfenstine, Post-doctoral Fellow

Graduate Research Assistants

James Proft, M.S. degree

Jerome P. Wittenauer, Ph.D. degree

Glenn Daehn, Ph.D. degree

Shyong Lee, Ph.D. degree